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Shipboard sea state estimation based on wave induced response measurements

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Shipboard sea state estimation based on wave-induced response measurements

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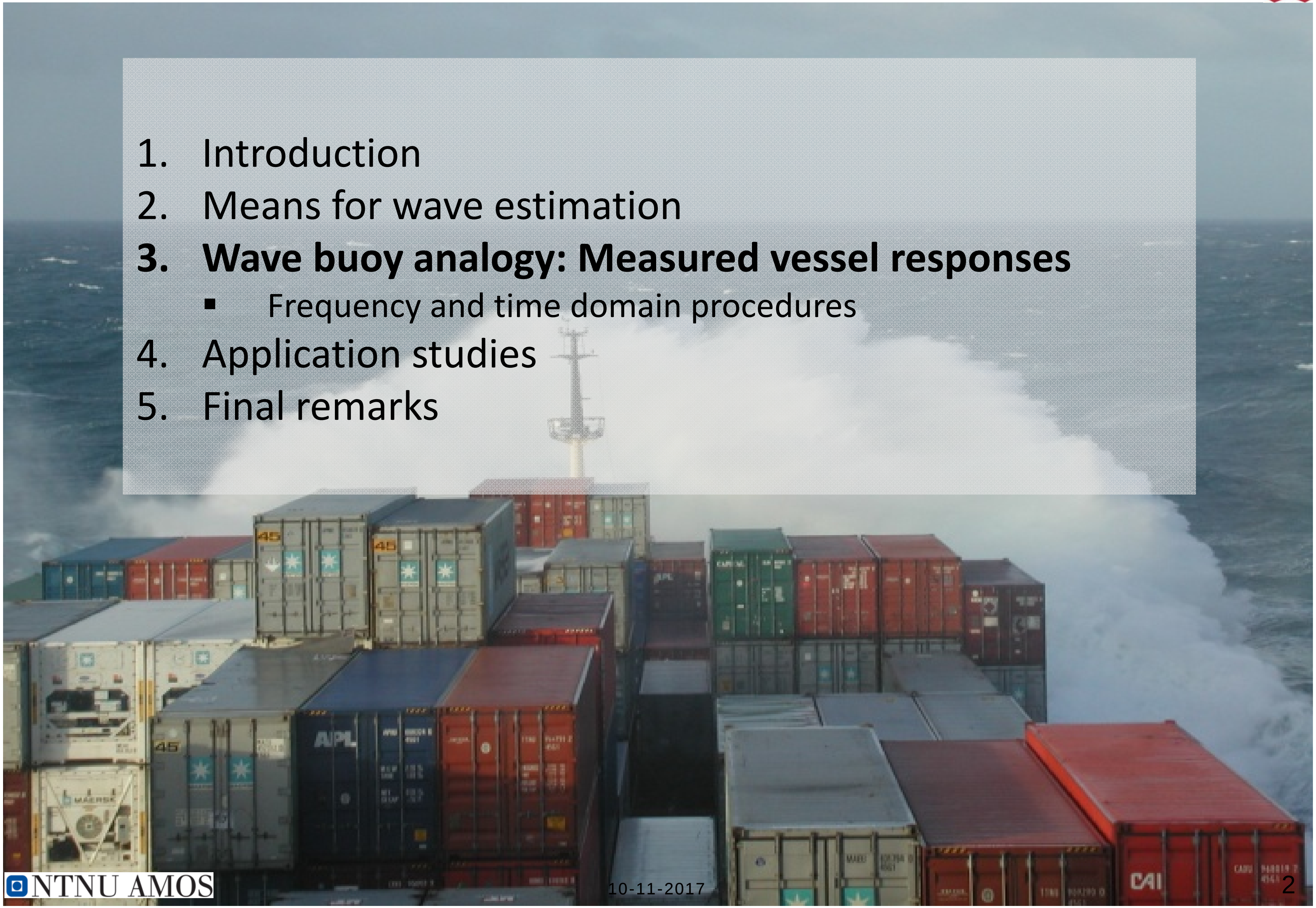
Agenda



1. Introduction
2. Means for wave estimation
3. **Wave buoy analogy: Measured vessel responses**
    - Frequency and time domain procedures
4. Application studies
5. Final remarks

Introduction: Areas of interest

DTU

Shipboard sea state estimation is relevant for, e.g.:

- **Safety of ships in transit and marine operations**: Structural integrity including fatigue damage; damage/loss of cargo; crew/passenger (dis)comfort
- **Dynamic positioning**: Better station-keeping capabilities, increased trust in operational windows
- **Environmentally friendly shipping**: Reduced exhaust emissions; improved fuel-efficiency, vessel and fleet performance systems
- **Wave and ocean statistics**: Continuous improvement of wave-scatter diagrams, better and/or more specific design of marine systems

Safe navigation

Fuel saving

Fatigue accumulation

Marine Operations

Sloshing avoidance

Introduction: Context

Deterministic and statistical *short-term* response predictions

- ***Deterministic predictions*** **→ 5 – 90 *seconds* ahead of instantaneous measurements; the actual response record is determined**

Heave compensation, helicopter landings, ...

- ***Statistical predictions*** **→ 10 – 90 *minutes* ahead of instantaneous measurements; statistics of the response record is determined**

Vessels in transit, risk avoidance...

Introduction: Application to DSS

Decision support systems

- **Monitoring**: Displays weather and wave environment, motions, accelerations, hull girder strains, etc.
- **Statistical guidance**: Safe and efficient speed and course options.
- **Deterministic predictions**: What happens here-and-now

From K. Bendix , 05-03-2012 @ Skibsteknisk Selskab

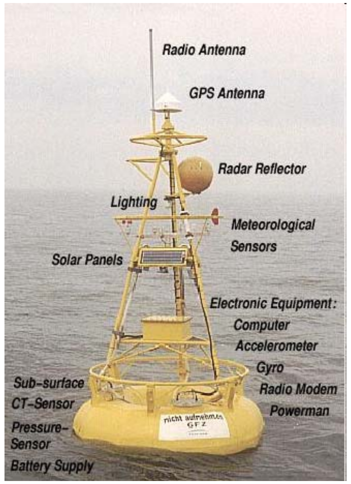
❑ **Information about waves (= the sea state) is fundamental (or at least very valuable) to conduct safe and efficient marine operations!**

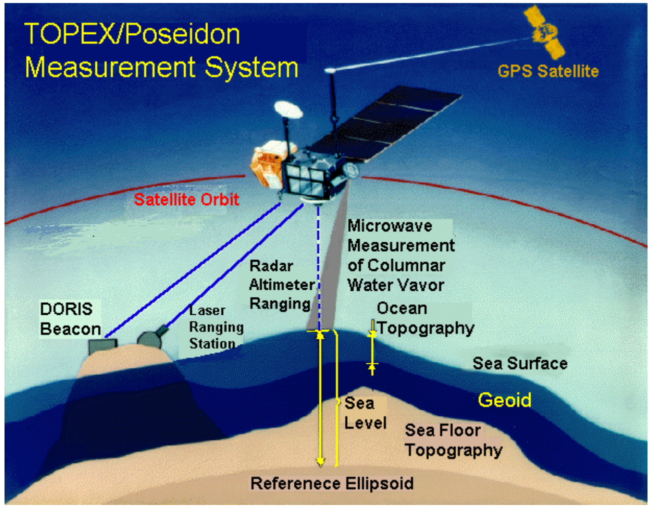
Means for wave estimation (1/2)

Well-known "typical" means to estimate sea states/wave energy spectra:

- Wave rider buoys, satellite measurements, and wave radars
- Note, shipboard DSS requires the sea state to be continuously (10-20 min. basis) updated at the exact position of the moving vessel!

- **Wave buoys**; wave-induced motion (3 translations and 3 rotations) 'transformed' into measurements of wave
- Suffers from being at a fixed position, and the information from wave buoys is scars in many parts of the oceans.

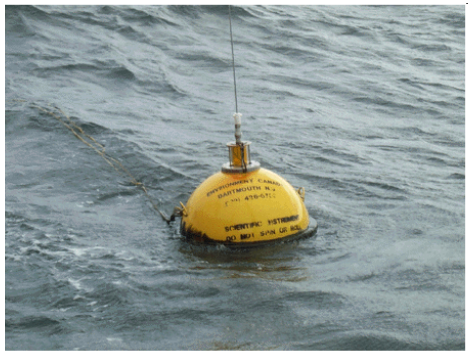




- **Satellite measurements;** valuable tool for statistics of ocean wave systems
- Processing time is (too) long i.e. satellite measurements are not applicable to DSS (yet...)

Means for wave estimation (2/2)

- **Wave radar systems** provide sea state in real-time and the exact position of the vessel.
- Accurate and reliable on period and direction but not always on wave height
- Systems are somewhat expensive and require careful calibration.



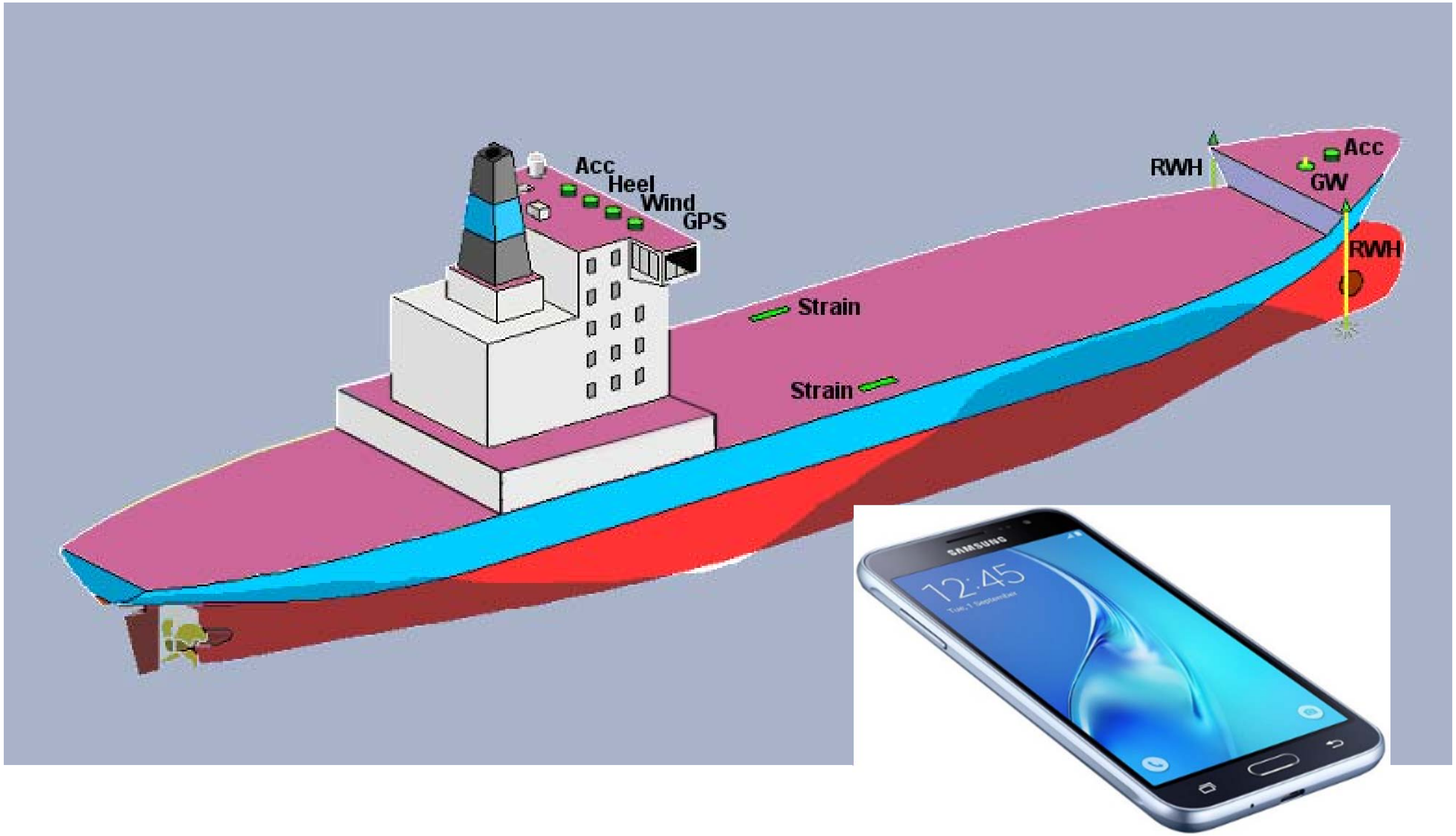
A wave buoy is a *floating structure*; and so is any type of ship... *The wave buoy analogy*

- Making use of available sensor recordings, i.e. no additional instrumentation or hardware
- Requires little calibration

Wave buoy analogy

Sea state estimation based on measured ship responses

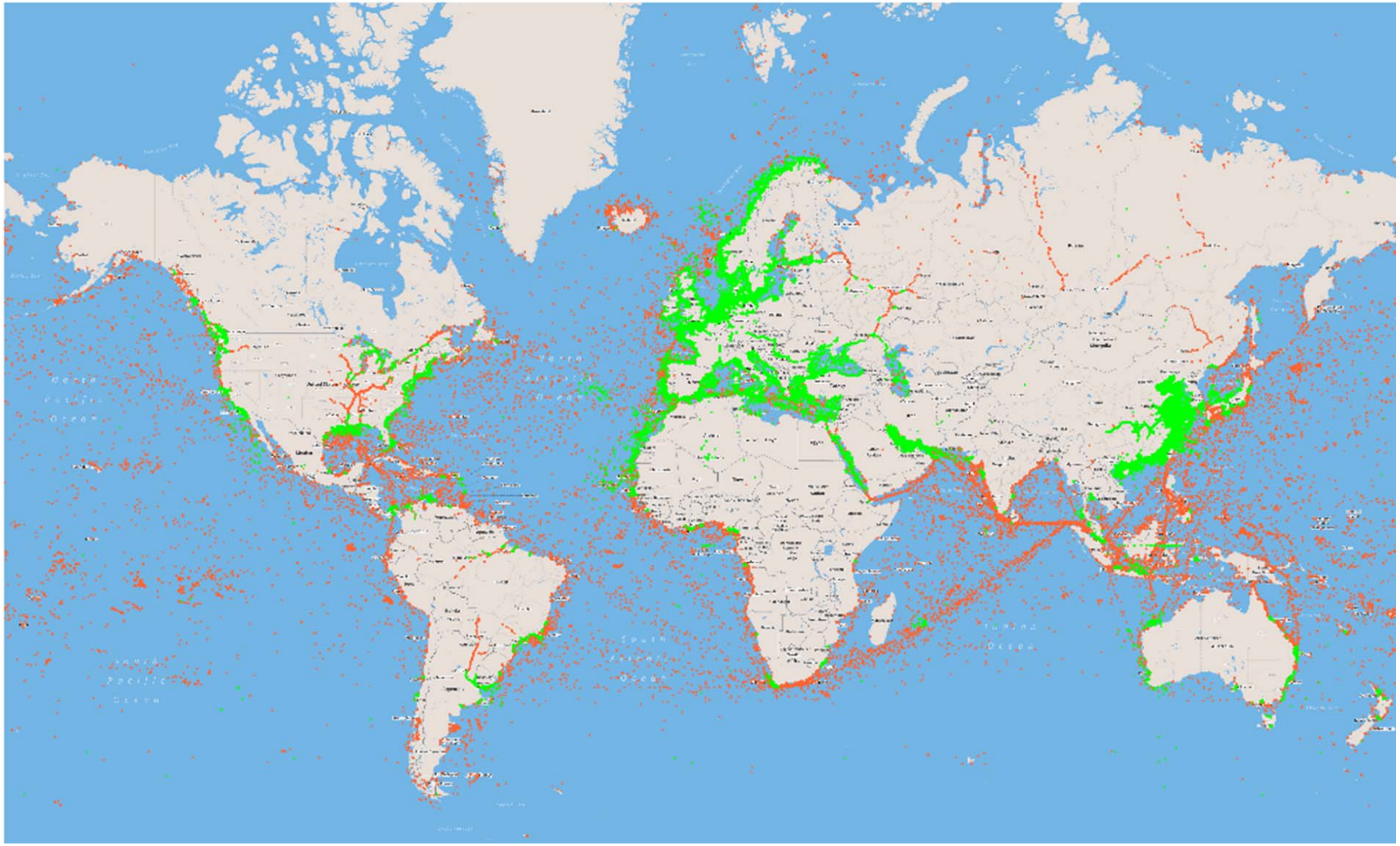
(recordings from a number of sensors...)



The future **Motion Response Unit**...

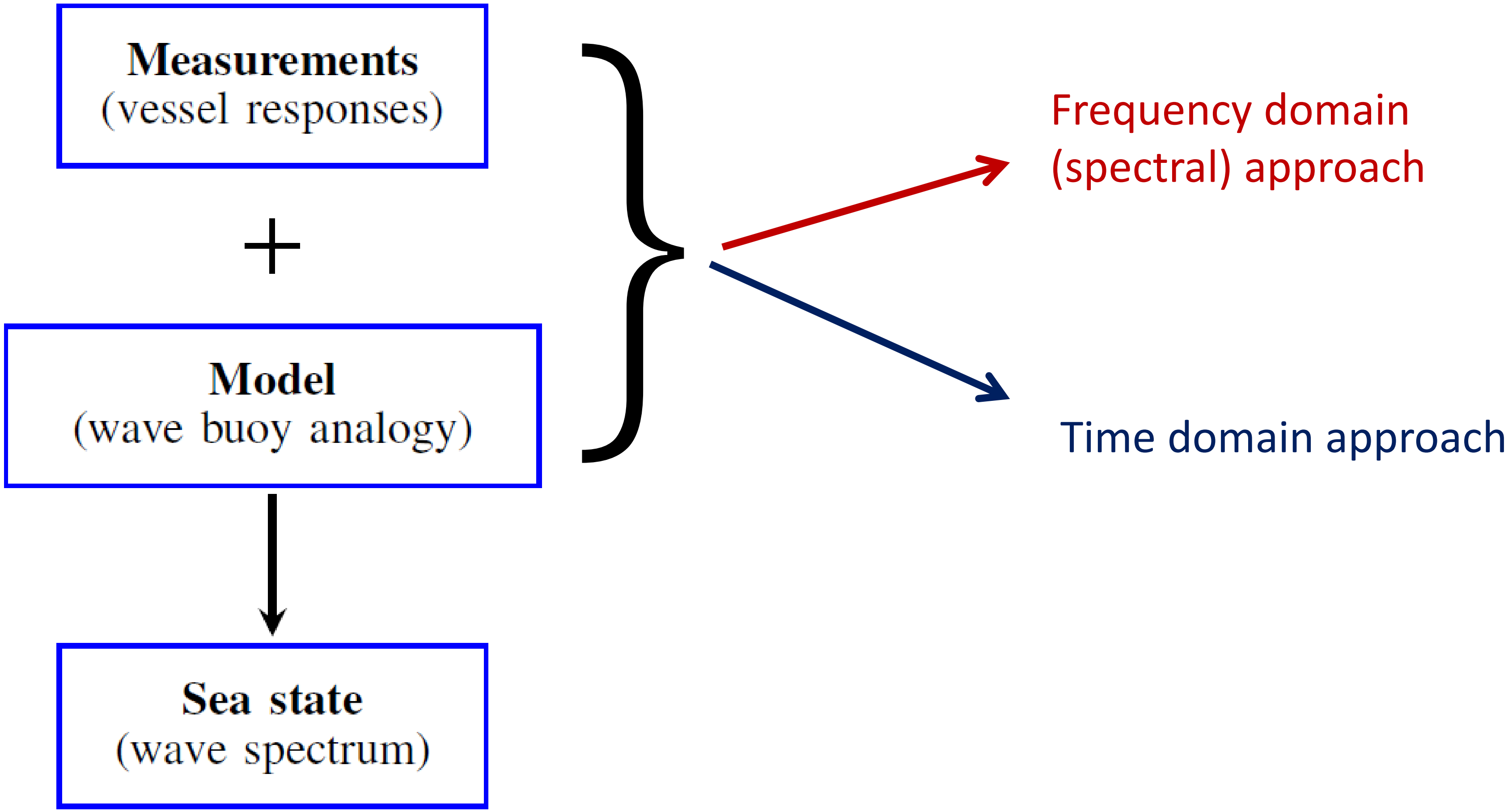
Why the wave buoy analogy?

The amount of wave-induced data from vessels is huge...



A **snapshot of vessel positions around the world's ocean** based on AIS data (green: terrestrial, red: satellites) url: https://www.fleetmon.com/global-vessel-coverage/

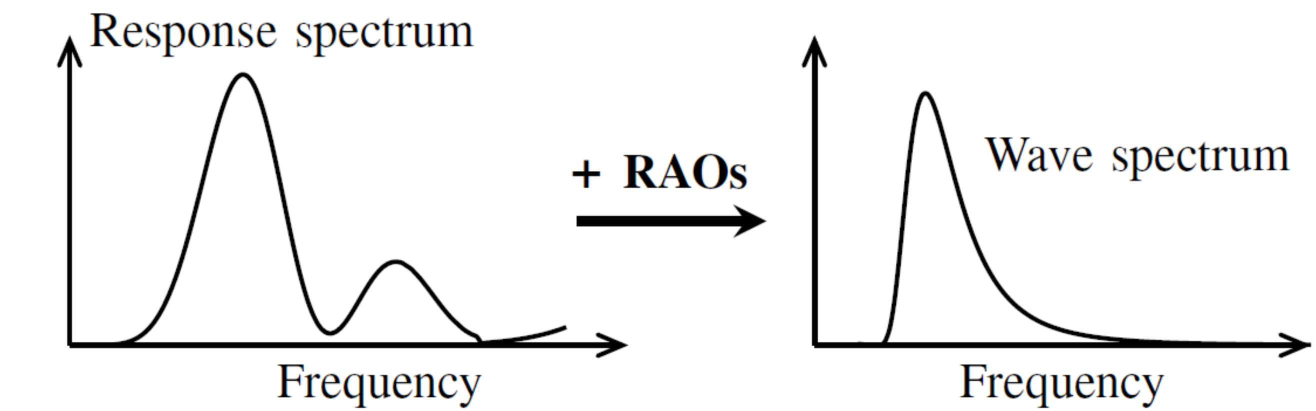
Basic principle



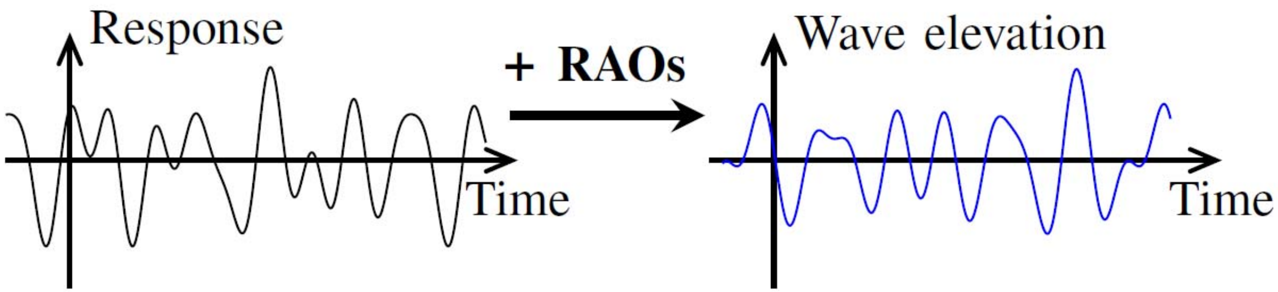
Basic principle, cont'd

The wave buoy analogy is formulated in one of two domains:

Frequency domain (spectral approach):



Time domain:

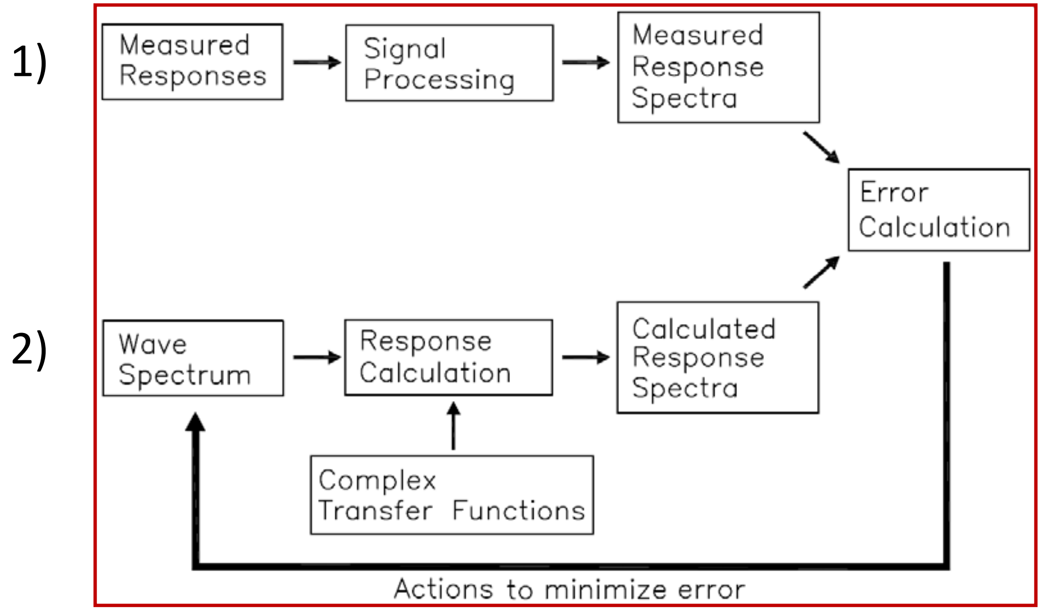


Basic principle, cont’d

Note, in either case a set of **complex-valued transfer functions is introduced**
(for the particular wave-induced responses)

- The majority of past work is focused on formulations in the frequency domain. NB. Strictly said, stationary conditions must apply.
- Time domain procedures can be formulated to relax the assumption about stationary conditions... work is still needed

Wave buoy analogy: Frequency domain procedures



1) Measurements: from measured ship responses, response spectra are derived.

2) Calculations: by combination of a wave spectrum and linear transfer functions of the responses, response spectra are *calculated*.

- **Assumption**: Linear relationship between wave excitations and ship responses ⟶ i.e. wave-vessel transfer functions are used.

- Representations by parametric and non-parametric modelling and a novel 'brute-force residual-based' approach. Several studies have been made. Solutions exist with and without forward speed.

- Note: Estimations are, in theory, less reliable during severe sea states (non-linearity between excitations and responses...), but in practice...

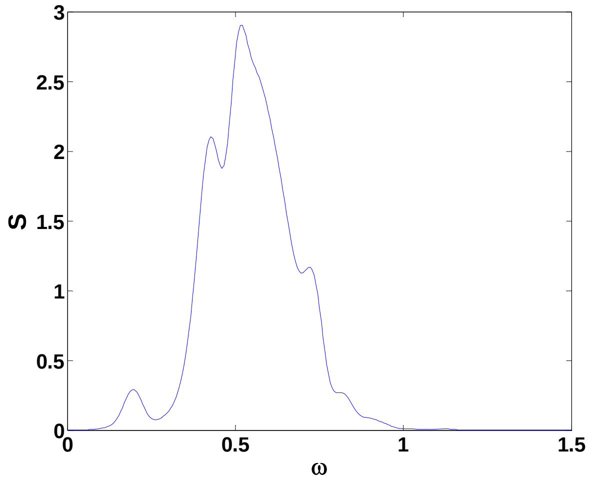
An illustration (1/2)

Calculation of wave-induced responses:

Theoretically calculated

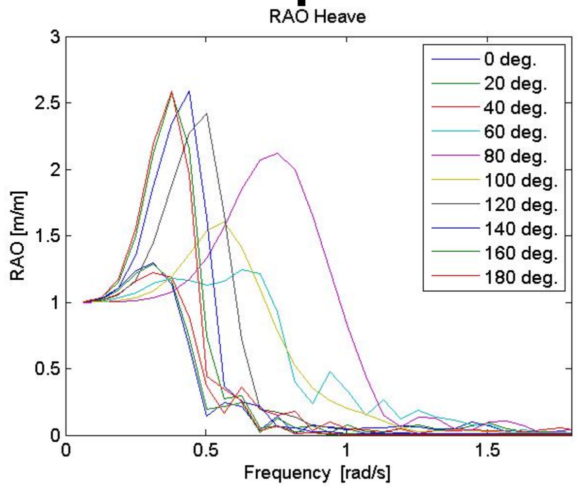
Wave spectrum + Transfer functions → Response spectra

Input



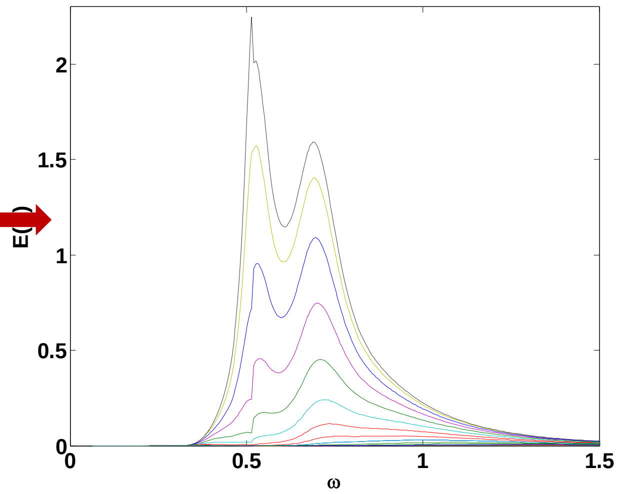
+

Input



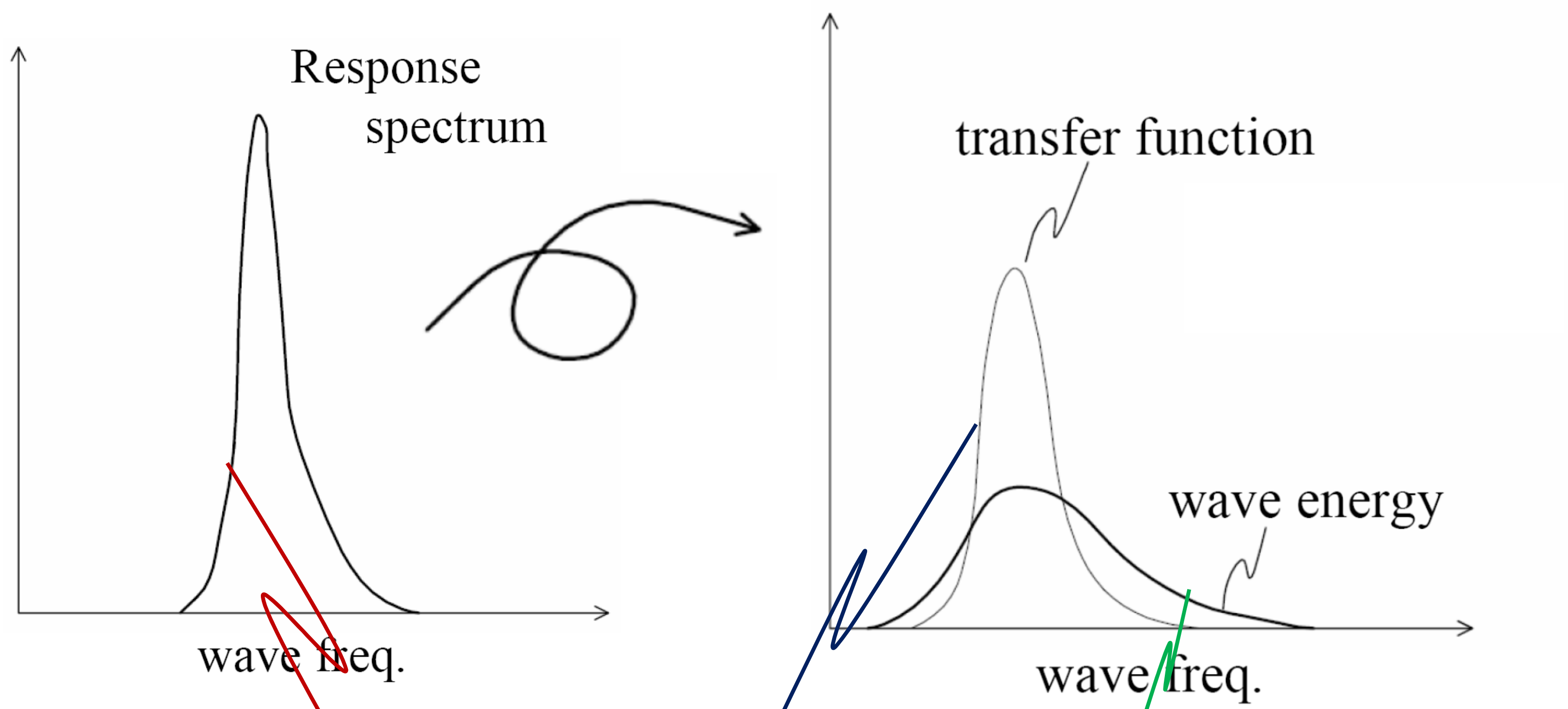
→

Output



An illustration (2/2)

The "inverse" process - i.e. the wave buoy analogy:



$$S_{ij}(\omega_e) = \int_{-\pi}^{\pi} \Phi_i(\omega_e,\beta)\overline{\Phi_j(\omega_e,\beta)}E(\omega_e,\beta)\,d\beta$$

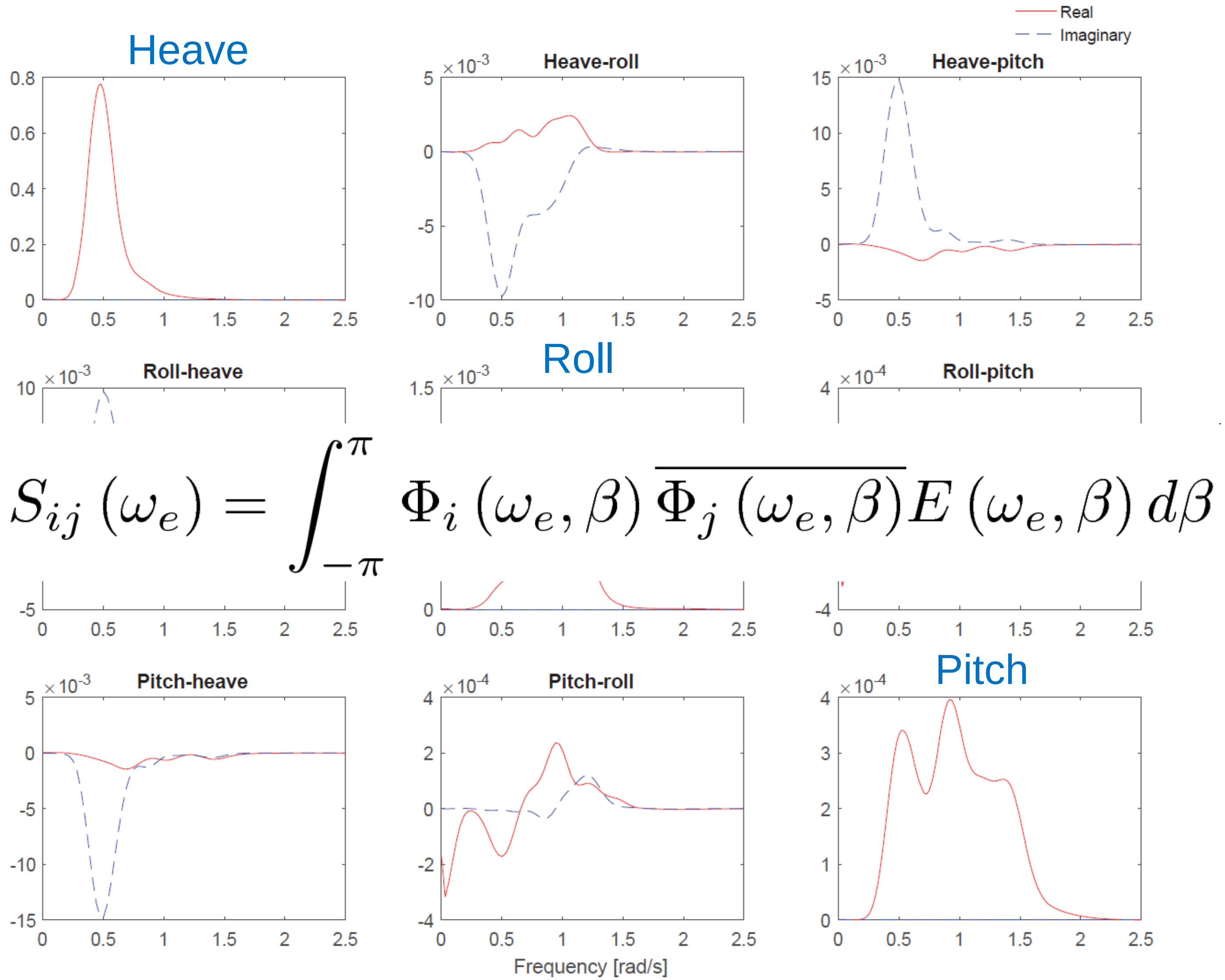
Measured

Theoretically calculated

Unknown

In practice

Three wave-induced responses are measured simultaneously:



$$S_{ij}\left(\omega_e\right) = \int_{-\pi}^{\pi} \Phi_i\left(\omega_e, \beta\right) \overline{\Phi_j\left(\omega_e, \beta\right)} E\left(\omega_e, \beta\right) d\beta$$

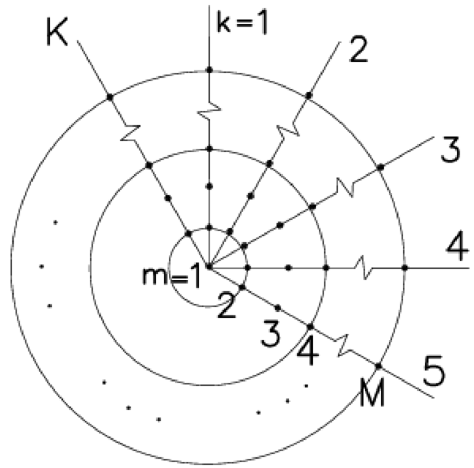
Figure 1: Cross spectra R_{ij} calculated from measured responses in heave [m], roll [rad.] and pitch [rad.] of the research vessel R/V Gunnerus. Brodtkorb et al. [14].

Modelling approaches in frequency domain

Three solution procedures:

1) **Non-parametric (Bayesian) modelling**

- In general, more unknowns than equations.
- Assumptions: 1) Introduction of the error as white noise (stochastic viewpoint); 2) Non-negativity constraint; 3) Introduction of prior information (~ 'Bayesian approach').



$\mathbf{f}(\mathbf{x}) = E(\omega, \beta)$

2) **Parametric modelling**

- Introduction of parameterised wave spectrum, e.g.:

$$E(\omega,\theta) = \frac{1}{4}\sum_{i=1}^{3} \frac{\left(\frac{4\lambda_i+1}{4}\omega_{p,i}^4\right)^{\lambda_i}}{\Gamma(\lambda_i)} \frac{H_{s,i}^2}{\omega^{4\lambda_i+1}} A(s_i)\cos^{2s_i}\left(\frac{\theta-\theta_{mean,i}}{2}\right)\exp\left[-\frac{4\lambda_i+1}{4}\left(\frac{\omega_{p,i}}{\omega}\right)^4\right]$$

- I.e., the solution is a set of optimised wave parameters.

Modelling approaches in frequency domain

3) **A brute-force residual-based calculation using an iterative scheme (Nielsen et al., 2017a)**

Measured (cross) spectrum of responses (i,j)

Error measure

$$\tilde{R}_{ij} = R_{ij}(\omega_e) - \hat{R}_{ij}$$

Estimated response spectrum (must be initialised)

$$\hat{E}_{ij}(k) = \hat{E}_{ij}(k) + h\tilde{R}_{ij}$$

$$\hat{R}_{ij} = \hat{E}_{ij}(k) \int \sum_{m=1}^{3} |\Phi_{ij}(\omega_{0m}, \mu + \chi_k)|^2 \varphi(\mu) d\mu$$

Estimated wave spectrum. NB: h is (positive-valued) increment.

Update response spectrum estimate

Modelling approaches in frequency domain

3) **A brute-force residual-based calculation using an iterative scheme (Nielsen et al., 2017a)**

$$\tilde{R}_{ij} = R_{ij}(\omega_e) - \hat{R}_{ij}$$

$$\hat{E}_{ij}(k) = \hat{E}_{ij}(k) + h\tilde{R}_{ij}$$

$$\hat{R}_{ij} = \hat{E}_{ij}(k) \int \sum_{m=1}^{3} |\Phi_{ij}(\omega_{0m}, \mu + \chi_k)|^2 \varphi(\mu) d\mu$$

The iteration continues until the error measure, $\tilde{R}_{ij}$, attains a value below a specified threshold...

Wave buoy analogy: Time domain procedures

- Sea state estimations in frequency domain depend highly on the <u>spectral (response) analysis</u>.

- In principle, <u>stationary operational conditions</u> are necessary because a minimum time window (10-15 min.), is needed to obtain reliable results from the spectral analysis.

- In practice, conditions are <u>*not* stationary</u> because of a changing sea state and/or, more likely, as a result of speed or heading changes of the vessel.

- In turn, sea state estimates (or updates) will be "back-dated".

- Altogether, the sea state estimate may be <u>compromised</u>!

- Another approach: Sea state estimation in time domain! New and ongoing work on two different procedures: 1) Kalman filtering and 2) a stepwise procedure

Modelling approaches in the time domain

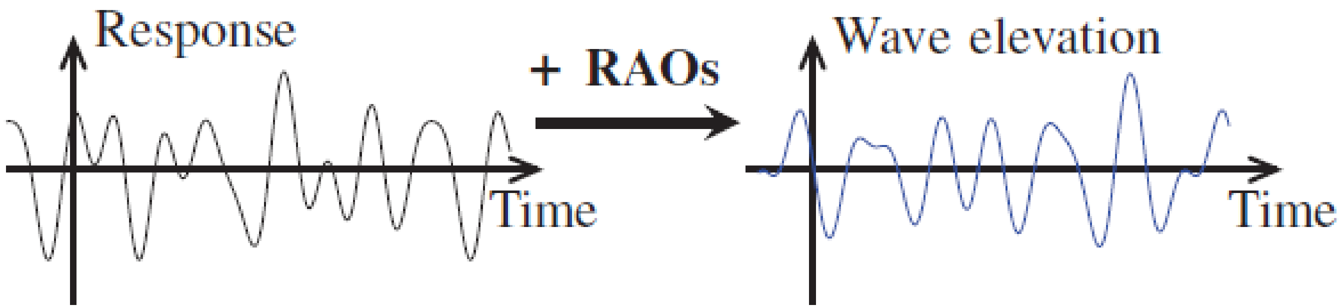


Figure 3: *Conceptually, the wave buoy analogy can be formulated directly in the time domain to give the actual wave elevation at the site of the vessel.*

The theoretical models; considering only one wave component:

Wave elevation:

$$\zeta(t) = \zeta_a \cos(\omega t + \varepsilon) = Re\left[(x_1 + i x_2)e^{i\omega t}\right]$$

Response:

$$R(t) = Re\left[(H(\omega) + iH(\omega))(x_1 + i x_2)e^{i\omega t}\right] \quad \text{Eq. (A)}$$

Modelling approaches in the time domain

1) Kalman filtering:

- The in-phase and quadrature components (x_1,x_2) are introduced as the states at discrete time *k*

$$\text{State Equation:} \quad \begin{cases} x_1(k+1) = x_1(k) + \xi_1(k) \\ x_2(k+1) = x_2(k) + \xi_2(k) \end{cases}$$

- The measurement equation follows directly from Eq. (A) on slide 14:

$$\begin{aligned} \text{Output Equation:} \quad z(k) = {} & \left(\mathrm{Re}\{H(\bar{\omega})\}\cos(\bar{\omega}kT_s) - \mathrm{Im}\{H(\bar{\omega})\}\sin(\bar{\omega}kT_s)\right)x_1(k) \\ & - \left(\mathrm{Re}\{H(\bar{\omega})\}\sin(\bar{\omega}kT_s) + \mathrm{Im}\{H(\bar{\omega})\}\cos(\bar{\omega}kT_s)\right)x_2(k) + \theta(k) \end{aligned}$$

(“measurement eq.”)

- Formulated in a vector-setting, the *standard prediction and update cycles* of the Kalman filter are applied to solve for the set of states at any discrete time

Modelling approaches in the time domain

2) The stepwise procedure (Nielsen et al., 2015+2016):

- The method estimates, stepwise, (peak) frequency and, subsequently, wave amplitude and phase on batches of data (4-8 periods).
- For the single batch, nonlinear least squares (NLLS) fitting is used to fit a 'best average regular' wave.
- Updates made on at discrete times and, hence, the signal can be reconstructed.

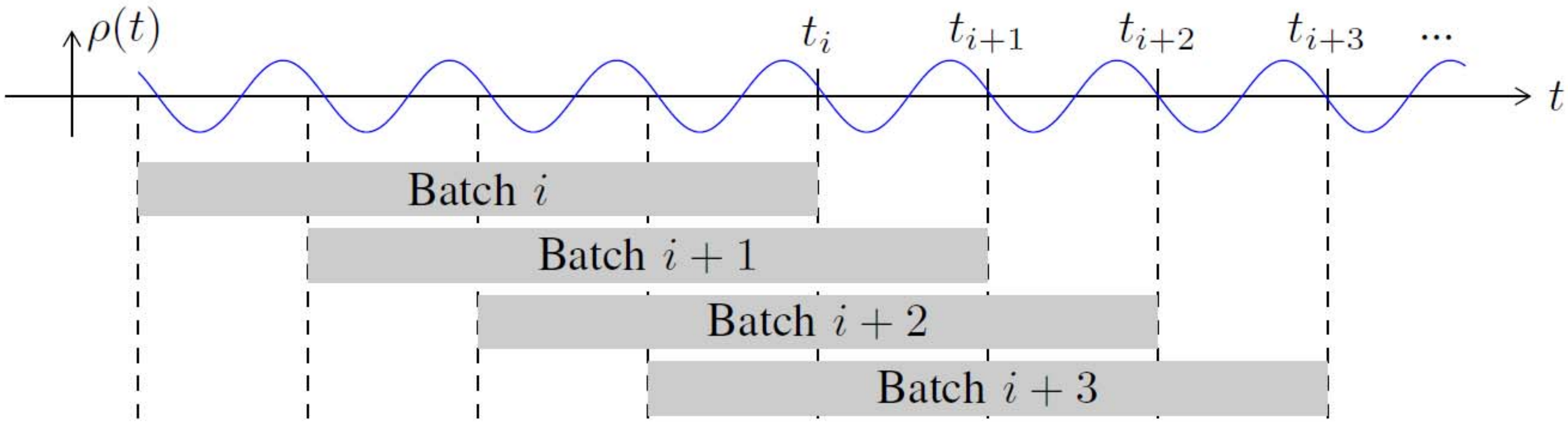
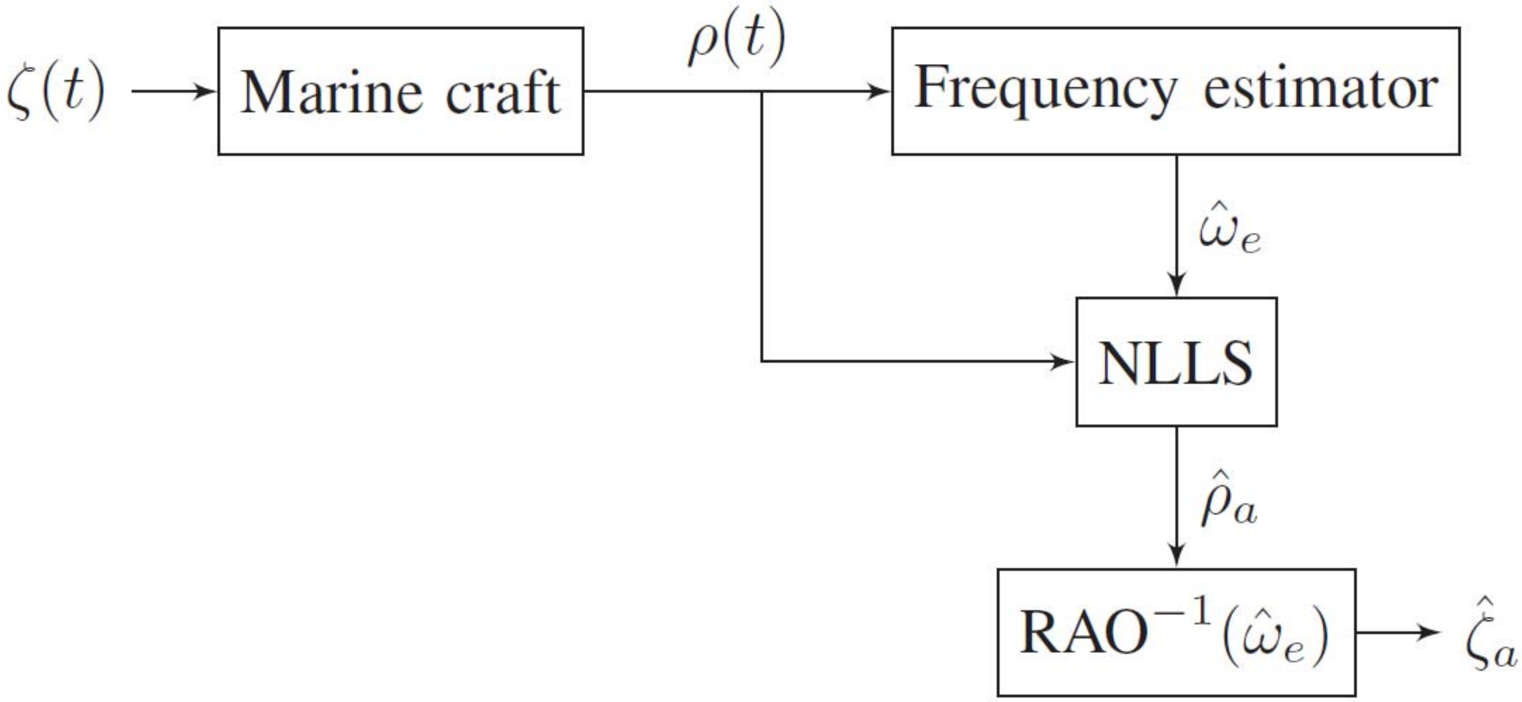


Figure 5: *Batch data with 75% overlap. Batch i is processed at time t_i.* [20]

Modelling approaches in the time domain

2) The stepwise procedure (Nielsen et al., 2015+2016):

- The method estimates, stepwise, (peak) frequency and, subsequently, wave amplitude and phase on batches of data (4-8 periods)..

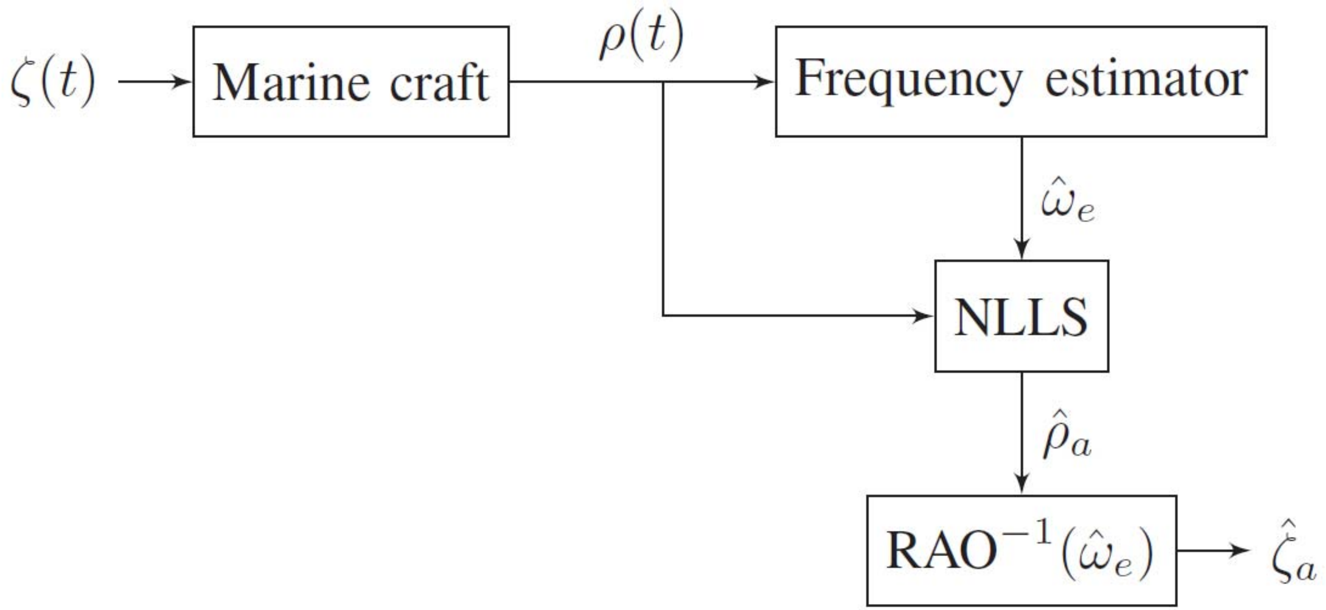


Modelling approaches in the time domain

2) The stepwise procedure (Nielsen et al., 2015+2016):

- The method estimates, stepwise, (peak) frequency and, respectively, wave amplitude and phase on batches of data (4-8 periods).

- So far **<u>only regular (sinusoidal) waves</u>** can be considered.



Application studies

✓ Frequency domain procedures are <u>well-tested</u> with both simulated data and full-scale measurements:

1) Dedicated sea trials (APOR'12)
2) In-service container vessel (PRADS'13)
3) Dedicated sea trials (ICASSP'18)

❖ Time domain procedures have been tested only using numerical simulations*:

1) Kalman filtering at zero-forward speed; with forward speed results are developed only for head sea
2) Stepwise (NLLS) procedure only for regular waves at zero-forward speed

- PhD work (proposal) to address specifically these issues

* Limited literature shows results with experimental data.

Dedicated sea trials (APOR'12)

Full-scale measurements from sea trials (DRDC)

Fig. 2: The Canadian Navy research ship CFAV Quest.
(L = 71.6 m, B = 12.8 m, T = 4.8 m, C_b = 0.51)

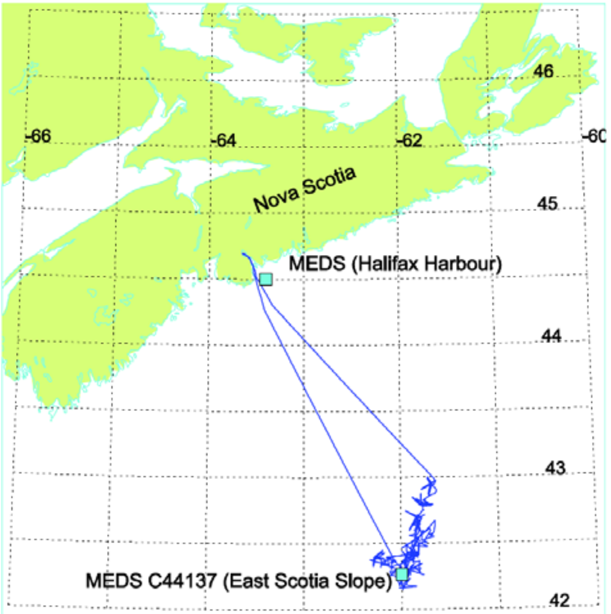


Fig. 3: Voyage map of sea trials.

- Responses: roll rate, roll angle, pitch rate, pitch angle, horizontal acc. and vertical acc. (all recorded at bridge).
- Ship motions calculated in-house by DRDC (SHIPMO7) using 2D strip theory
- Sea state monitored continuously by three wave buoys (MEDS C44137 and two drifting Triaxys buoys)
- 16 sets of trials, all with identical "relative" run patterns

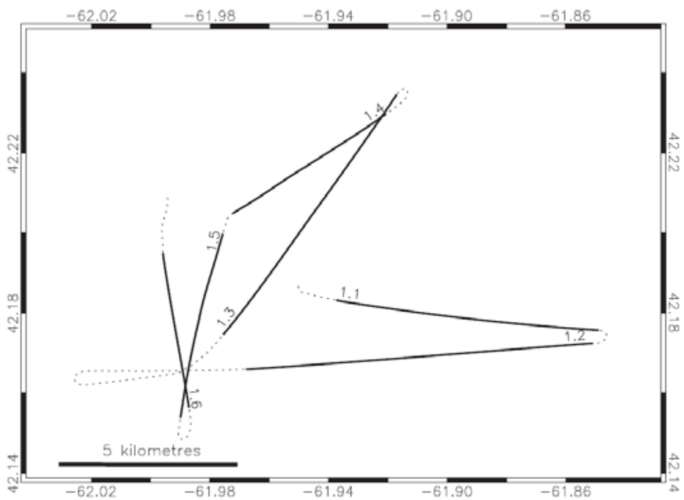
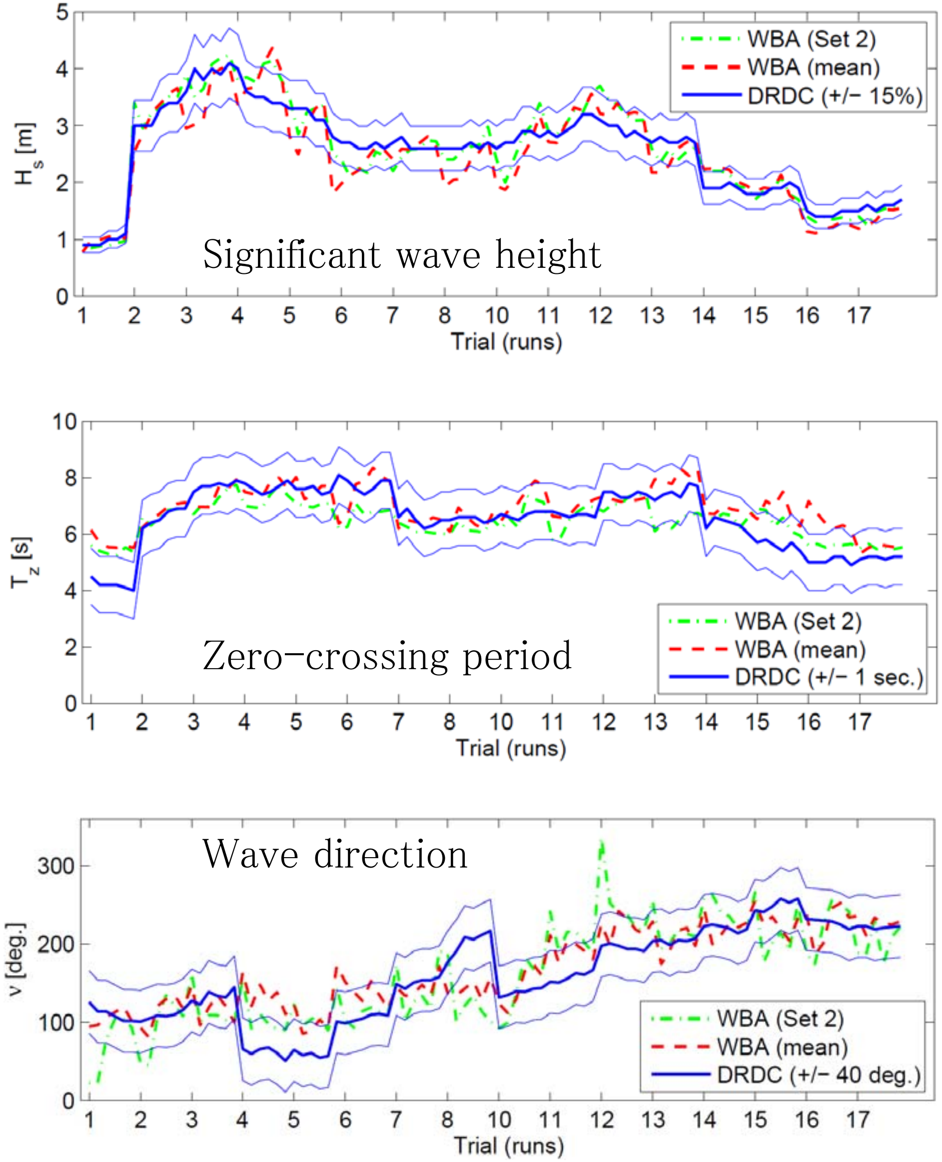


Fig. 4: Run pattern of trial no. 1.

Dedicated sea trials (APOR'12)

Full-scale measurements from sea trials (DRDC)



WBA: Results by wave buoy analogy (parametric modelling). NB. Combination of different sets of motion responses.

DRDC: Results obtained as the weighted average value of three floating wave rider buoys.

Full-scale response measurements (PRADS'13)

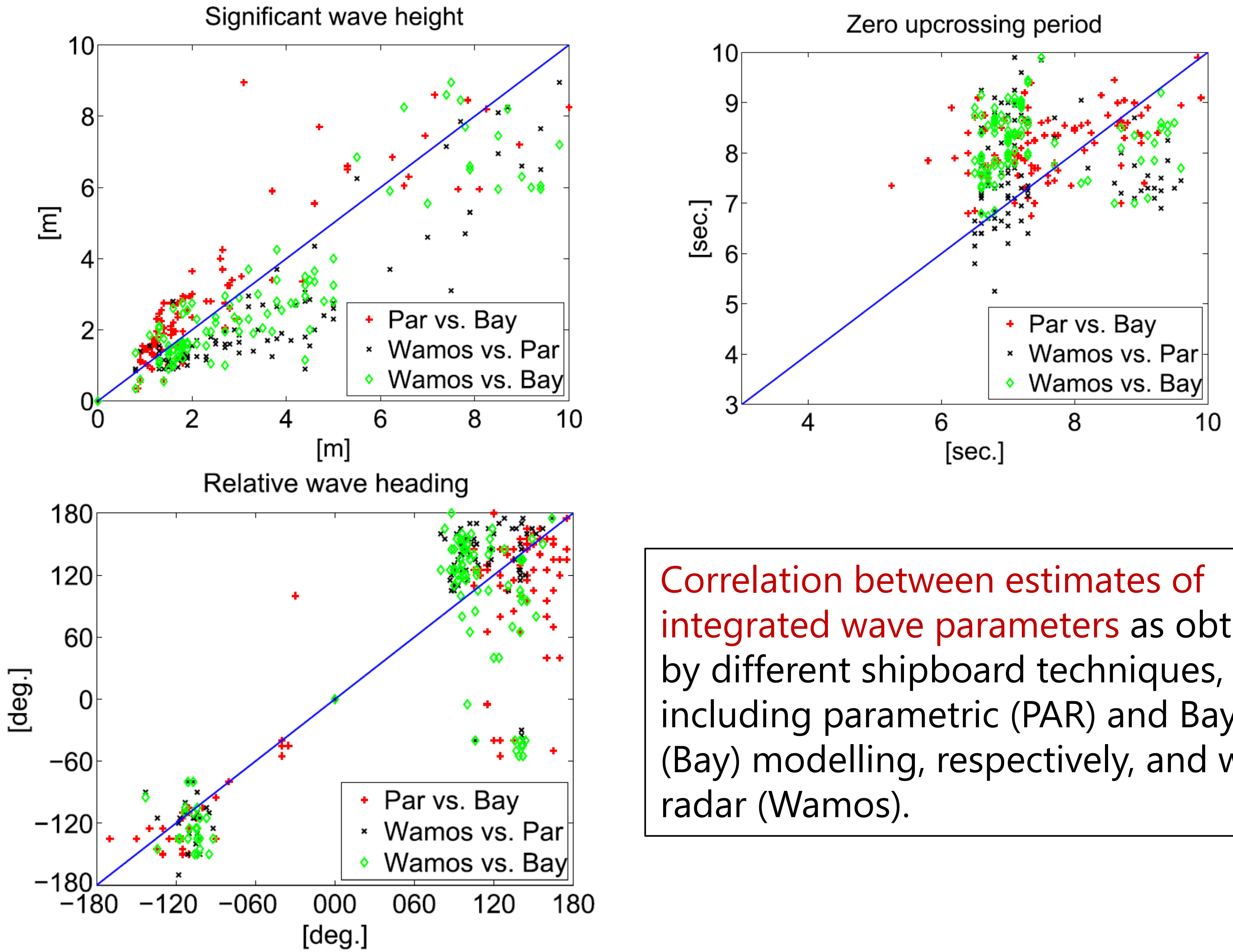
Table 1: Main dimensions of ship.

Parameter	Dimension
L_{OA}	349.0 m
Beam	42.8 m
Draught	15.0 m
DWT	113,000 ton

Vessel responses:

- motions (sway, heave, roll, and pitch)
- accelerations
- dist. to sea surface
- strains

Full-scale response measurements (PRADS'13)

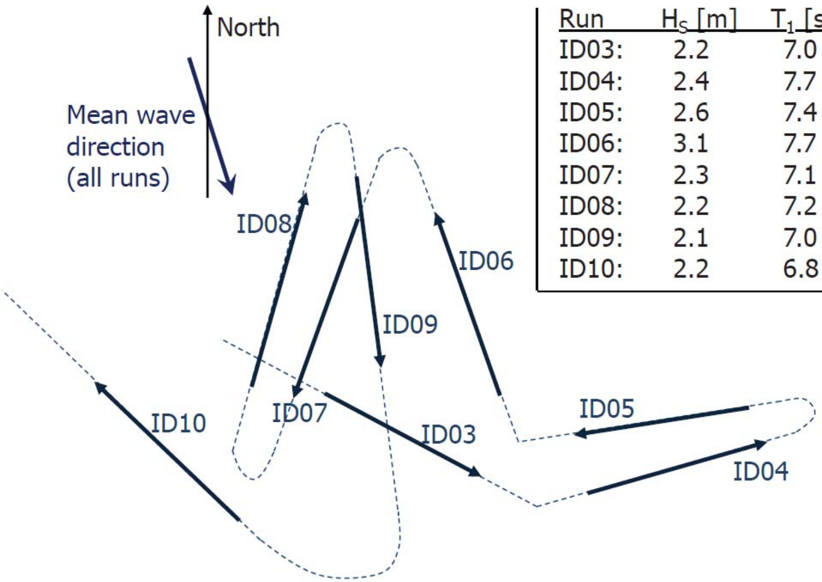


Correlation between estimates of integrated wave parameters as obtained by different shipboard techniques, including parametric (PAR) and Bayesian (Bay) modelling, respectively, and wave radar (Wamos).

Dedicated sea trials (ICASSP’18)

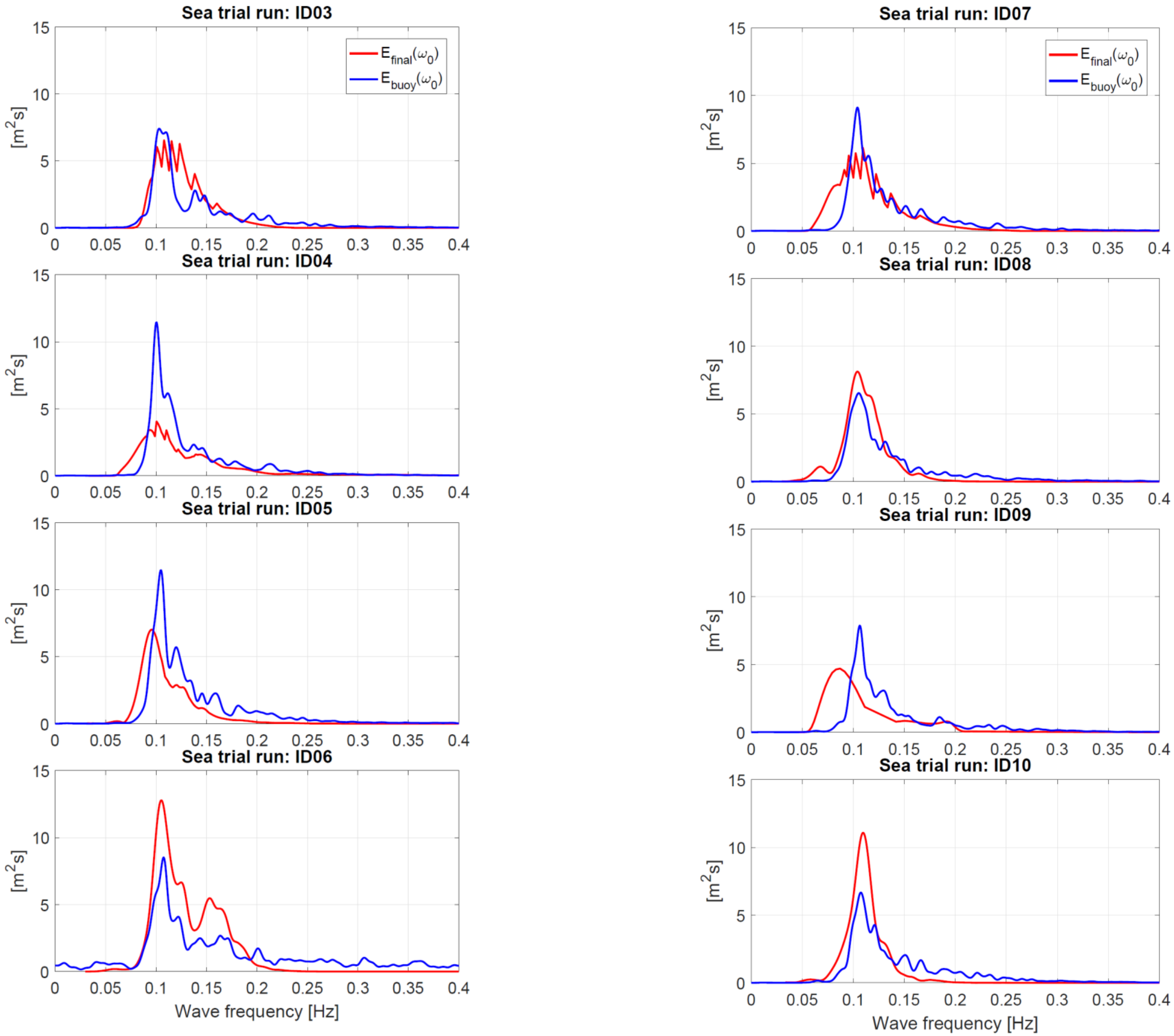
Table 1. Main parameters of research vessel (R/V Gunnerus).

Length, L_{pp}	28.9 m
Breadth, B	9.6 m
Draught, T	2.7 m
Block coefficient, C_B	0.56 [-]
Waterplane coefficient, C_{WP}	0.84 [-]
Displacement, Δ	417 000 kg
Transverse metacentric height, GM_T	2.66 m



Run	H_S [m]	T_1 [s]	θ [°]
ID03:	2.2	7.0	342
ID04:	2.4	7.7	343
ID05:	2.6	7.4	346
ID06:	3.1	7.7	346
ID07:	2.3	7.1	338
ID08:	2.2	7.2	342
ID09:	2.1	7.0	323
ID10:	2.2	6.8	349

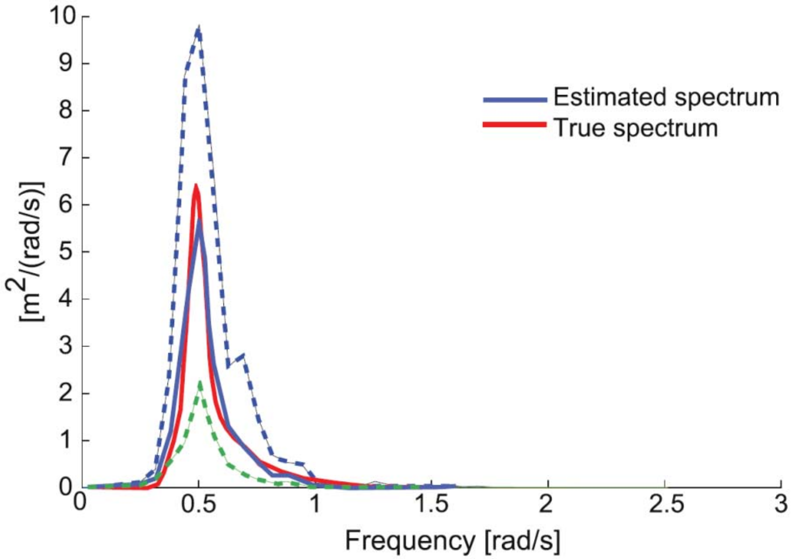
Dedicated sea trials (ICASSP'18)



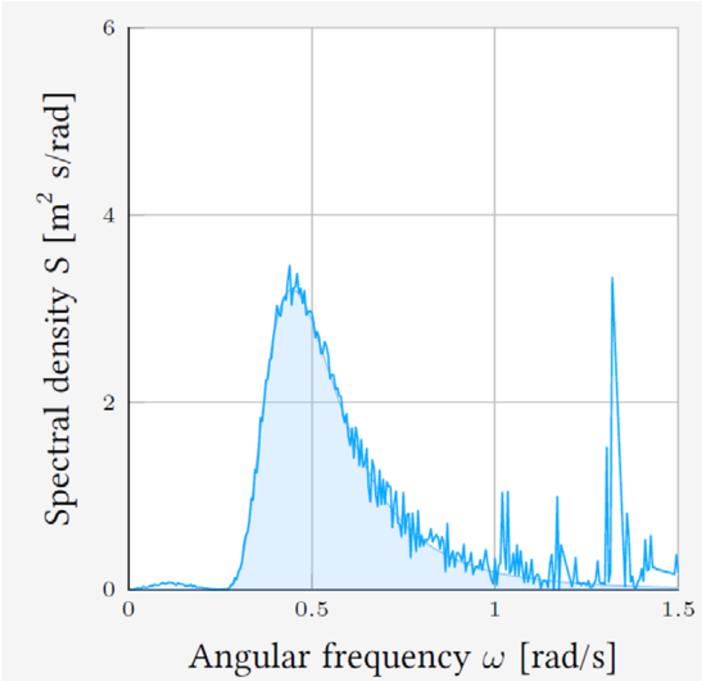
Time domain procedures

÷ Time domain procedures still need further developments, but promising results have been obtained from simulations

Wave estimation using Kalman filtering:



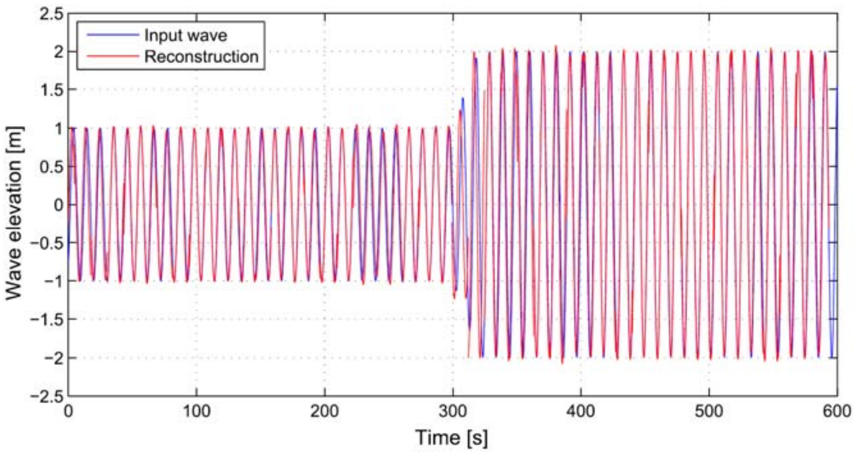
Full lines indicate 'average spectrum', while dashed lines represent lowest and highest energy content in estimated spectrum, obtained from fifty sets of estimations



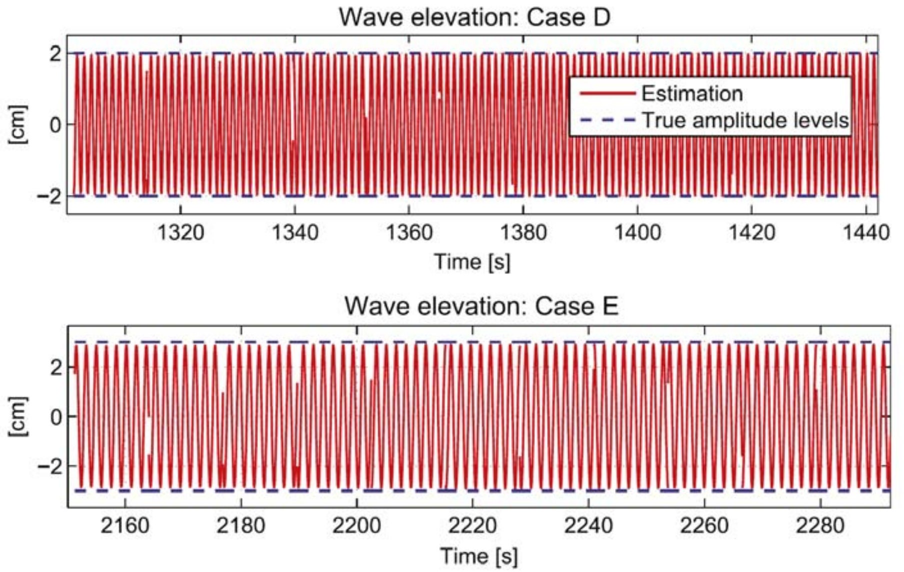
With forward speed...

Time domain procedures

Nonlinear least squares fitting:



Reconstruction of wave elevation process, running (near) real-time. **Simulations**.
Nielsen et al. (2015)



Model-scale experiments
Nielsen et al. (2016)

Conclusions and further work

- Well-established procedures – in the frequency domain – for sea state estimation; NB: stationary conditions must apply (in principle).
- It is necessary to (further) develop the wave buoy analogy in the time domain to handle truly nonstationary conditions.
- Wave parameter-estimations based entirely on measurements data (procedures exist already for peak period).
- Automatic selection of the best response combination under given operational conditions; a set of three is typically considered.
- Uncertainties are related to both measurements and transfer functions; i.e. uncertainty modelling should be considered to increase reliability.
- Fault-detection and fault-tolerant approaches
- Global network of 'wave recorders'; an enormous amount of wave data/statistics becomes available if all ships navigating the oceans collect data
- … …

Conclusions and further work

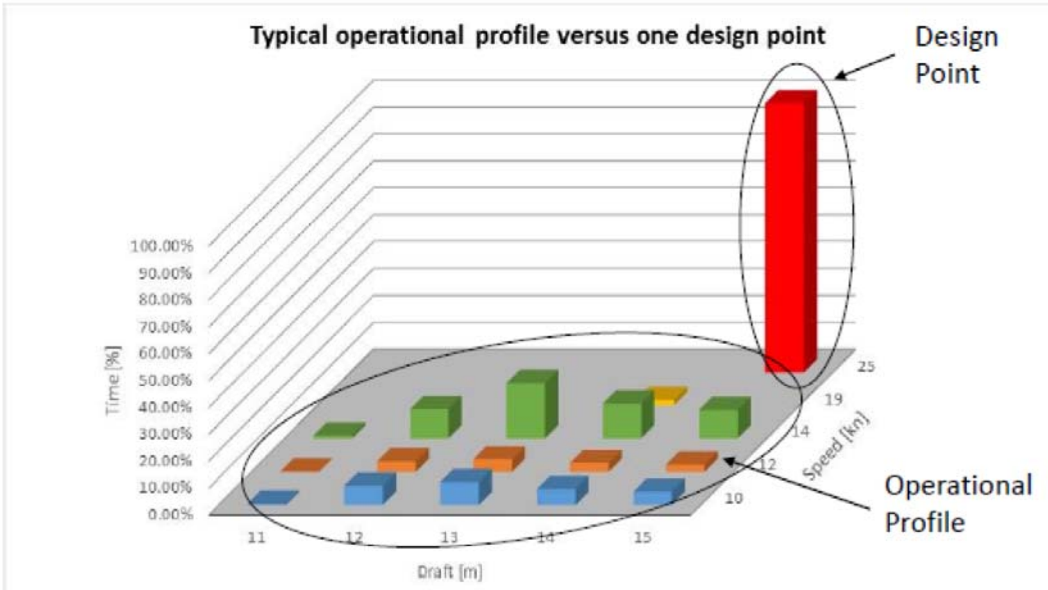
Other uses of shipboard SSE

- Study ships' operational profiles in a short-term sense and during their lifetime; do ships meet the wave scenarios as they were designed for?

- Added resistance in waves; improved models for added resistance in waves and experimental data is still scarce.

- Investigation of accidents; a sort of 'black box' could be installed on ships, like it is known from the aviation industry, making it easier to investigate weather- and wave-induced accidents.

- … …



Thank you

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